

D rare/forbidden decays at BESIII

MINGGANG ZHAO¹(FOR THE BESIII COLLABORATION)*School of Physics
Nankai University, Tianjin, 300071, P.R. China*

In this document we present the latest result on rare/forbidden decays for D mesons at the BESIII experiment. Based on 2.92 fb¹ data taken at the center-of-mass energy 3.773 GeV with the BESIII detector, the flavor-changing neutral current process $D^0 \rightarrow \gamma\gamma$ is searched using a double tag technique, while the decays of $D^+ \rightarrow h^\pm e^+ e^\mp$ (h stands for K or π) are studied based on a single tag method. The resulting upper limits are still above the Standard Model predictions.

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1 Introduction

One way to search for physics beyond the Standard Model is to search for decays that are forbidden or predicted to occur at a negligible level. Observing such decays would constitute evidence for new physics, and measuring their branching fractions would provide insight into how to modify our theoretical understanding. For example, the absence of flavor-changing neutral currents (FCNCs) in kaon decays led to the prediction of the charm quark [1], and the observation of $B^0 - \bar{B}^0$ mixing, a FCNC process, indicated a very large top-quark mass [2]. Till now, the rare and forbidden charm decays have been less informative and less extensively studied.

FCNC processes in charm decays are highly suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism [3], and can only occur via higher-order diagrams within SM, but the estimated branching fractions are 10^{-8} to 10^{-6} [4]. Such a small branching fractions are touching the sensitivity of current experiments. However, if additional new particles or mechanism exist, they could contribute additional amplitudes that would make these modes observable. Thus, the hints of D^+ FCNC decays might provide indication of non-SM physics or of unexpectedly large rates, such as at 10^{-5} or 10^{-6} level [5], for long-distance SM processes $D^+ \rightarrow \pi^+ V$, $V \rightarrow e^+ e^-$, with a real or virtual vector meson V (can be a ρ , ω , or ϕ). The LNV decays $D^+ \rightarrow K^- e^+ e^+$ and $D^+ \rightarrow \pi^- e^+ e^+$ are strictly forbidden in the SM. They could be induced by a Majorana neutrino, but with a branching fraction only of order 10^{-23} [6]. So any observation at experimentally accessible levels would be clear evidence of new physics. The searches for these decay modes have been carried out in several experiments (see table 1). In this document, we present latest results of searching for the FCNC decays of $D^0 \rightarrow \gamma\gamma$, $D^+ \rightarrow K^+ e^+ e^-$ and $D^+ \rightarrow \pi^+ e^+ e^-$ together with the lepton-number violating (LNV) decays of $D^+ \rightarrow K^- e^+ e^+$ and $D^+ \rightarrow \pi^- e^+ e^+$ at the BESIII experiment.

Table 1: Comparisons of the upper limits (10^{-6}) on the branching fractions for $D^+ \rightarrow h^\pm e^\mp e^+$ at a 90% C.L..

Experiments	$D^+ \rightarrow K^+ e^+ e^-$	$D^+ \rightarrow K^- e^+ e^+$	$D^+ \rightarrow \pi^+ e^+ e^-$	$D^+ \rightarrow \pi^- e^+ e^+$
CLEO [7]	-	-	2600	-
MARK2 [8]	4800	9100	2500	4800
E687 [9]	200	120	110	110
E791 [10]	200	-	52	96
CLEO [11]	3.0	3.5	5.9	1.1
Babar [12]	1.0	0.9	1.1	1.9
PDG [13]	1.0	0.9	1.1	1.1
This work	1.2	0.6	0.3	1.2

2 Technique

For the e^+e^- annihilation experiment around the $\psi(3770)$ peak, the D mesons are produced in pairs, i.e., if a D meson is reconstructed in an event, which is called a *singly tagged D event*, there must exist a \bar{D} meson in the recoiling side. If the pair $D\bar{D}$ is fully reconstructed in an event, the event is called a *doubly tagged $D\bar{D}$ event*. Traditionally, there are two methods to perform the searching for the rare/forbidden decays. One is based on singly tagged events which will provide large statistics with high backgrounds, another is using doubly tagged events presenting extremely low backgrounds while bad statistics (see table 2). On which technique a searching will employ depends on both background contaminations and the statistics.

Table 2: Two techniques on rare/forbidden searching.

Method	Statistics (charged/neutral)	Background	Sensitivity
Single Tag Method	$1.7 \times 10^7 / 2.1 \times 10^7$	not good	Bkg. vs Stat.
Double Tag Method	$1.6 \times 10^6 / 2.8 \times 10^6$	clean	Bkg. vs Stat.

3 $D^+ \rightarrow h^\pm e^+ e^\mp$

To searching the decays of $D^+ \rightarrow h^\pm e^+ e^\mp$, where h means K/π , we check the accepted events in the signal boxes in the scatter plots of M_{BC} versus ΔE which are shown in figure 1. The signal box, which are kept blind before cuts optimizing and backgrounds studies based on MC and sideband data, is defined with the mean value and the resolution of M_{BC} and ΔE determined from MC simulations, i.e. $|\Delta E - \Delta E_{\text{mean}}| < 3\sigma_{\Delta E}$ and $|M_{BC} - M_{D^+}| < 3\sigma_{M_{D^+}}$, where ΔE_{mean} is the mean value of the ΔE distribution, M_{D^+} is the D^+ nominal mass, $\sigma_{\Delta E}$ and $\sigma_{M_{D^+}}$ are the corresponding resolutions. Events falling into the signal box, shown as blue rectangle in figure 1, are taken as candidate signal events.

Table 3 summarizes the numbers of events inside ($N_{\text{inside}}^{\text{data}}$) and outside ($N_{\text{outside}}^{\text{data}}$) the signal boxes, the scale factors (f_{scale}), detection efficiencies (ϵ), systematic uncertainties (Δ_{sys}), calculated upper limits for the observed events (f_{90}) and branching fractions (\mathcal{B}). The upper limits on the numbers of these decays is determined by utilizing a frequentist method [14] with unbounded profile likelihood treatment of systematic uncertainties, where the number of the observed events is assumed to follow a Poisson distribution, the number of background events and the efficiency are assumed to follow Gaussian distributions, and the systematic uncertainty is considered as the standard deviation of the efficiency. Our results for $D^+ \rightarrow \pi^+ e^+ e^-$ and $D^+ \rightarrow K^- e^+ e^+$ are significantly improved than the previous restrictions and the other two limits are comparable with the world best results.

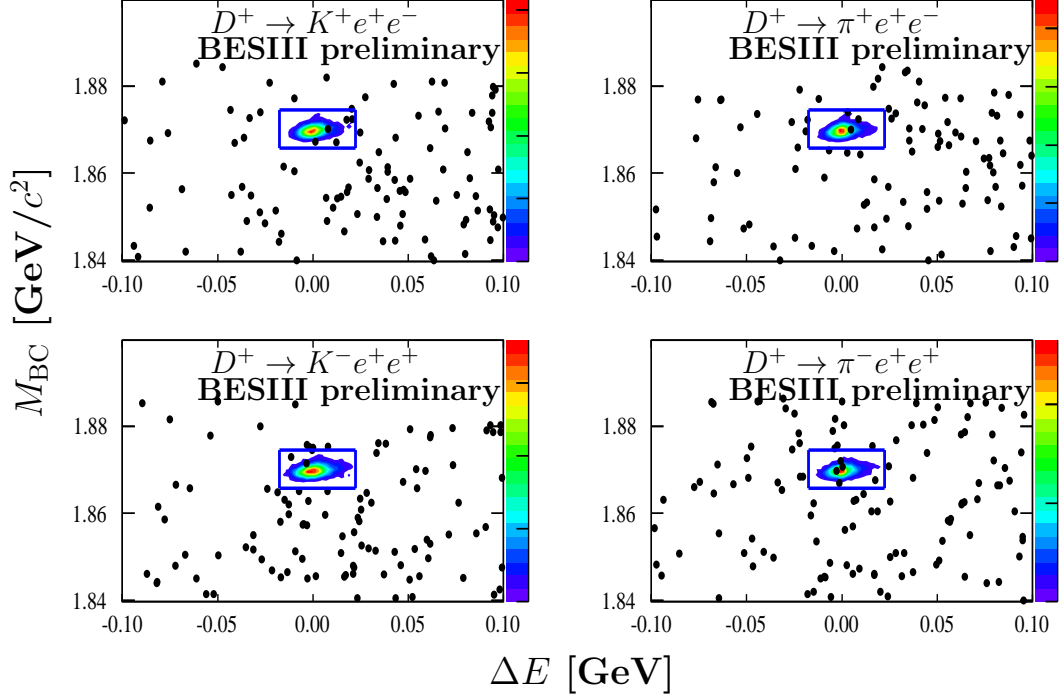


Figure 1: The scatter plots of M_{BC} versus ΔE of the accepted events in data, where the blue rectangle denotes the signal box. The contour plot is determined by MC simulations. The scale of the MC is arbitrary.

Table 3: Summary of the numbers.

	$N_{\text{inside}}^{\text{data}}$	$N_{\text{outside}}^{\text{data}}$	f_{scale}	ϵ [%]	Δ_{sys} [%]	f_{90}	$\mathcal{B} [\times 10^{-6}]$
$D^+ \rightarrow K^+ e^+ e^-$	5	69	0.08 ± 0.01	22.53	5.4	19.4	< 1.2
$D^+ \rightarrow K^- e^+ e^+$	3	55	0.08 ± 0.01	24.08	6.1	10.2	< 0.6
$D^+ \rightarrow \pi^+ e^+ e^-$	3	65	0.09 ± 0.02	25.72	5.9	4.2	< 0.3
$D^+ \rightarrow \pi^- e^+ e^+$	5	68	0.06 ± 0.02	28.08	6.8	20.5	< 1.2

4 $D^0 \rightarrow \gamma\gamma$ [15]

To suppress the backgrounds from QED continuum processes, potential $\psi(3770) \rightarrow$ non- $D\bar{D}$ decays, as well as D^+D decays, we perform a double tag technique in the analysis. In this work, singly tagged events are selected as the first step, then $\gamma\gamma$ final states will be investigated in the system recoiling side.

Single tag candidates are selected by reconstructing a \bar{D}^0 in one of the following five hadronic final states: $\bar{D}^0 \rightarrow K^+\pi$, $K^+\pi\pi^0$, $K^+\pi\pi^+\pi$, $K^+\pi\pi^+\pi\pi^0$, and $K^+\pi\pi^0\pi^0$, constituting approximately 37% of all D^0 decays [16]. The absolute branching fraction for the signal mode is determined as,

$$\mathcal{B} = \frac{N_{\text{tag},\gamma\gamma}}{\sum_i N_{\text{tag}}^i \cdot (\epsilon_{\text{tag},\gamma\gamma}^i / \epsilon_{\text{tag}}^i)}, \quad (1)$$

where i runs over each of the five tag modes, N_{tag} and ϵ_{tag} are the single tag yield and reconstruction efficiency, and $N_{\text{tag},\gamma\gamma}$ and $\epsilon_{\text{tag},\gamma\gamma}^i$ are the yield and efficiency for the double tag combination of a hadronic tag and a $D^0 \rightarrow \gamma\gamma$ decay.

We extract the single tag yield for each tag mode and the combined yields of all five modes from fits to $M_{\text{BC}}^{\text{tag}}$ distributions. The signal shape is derived from the MC simulation which includes the effects of beam-energy smearing, initial-state radiation, the $\psi(3770)$ line shape, and detector resolution. We then convolute the line shape with a Gaussian to compensate for a difference in resolution between data and our MC simulation. Mean and width of the convoluted Gaussian, along with the overall normalization, are left free in our nominal fitting procedure. The background is described by an ARGUS function [17], which models combinatorial contributions. In the fit, all parameters of the background function are left free, except its endpoint which is fixed at 1.8865 GeV/ c^2 . Figure 2 shows the fits to our tag-candidate samples.

Although we can suppress most of the background with the double tag method, there remain residual contributions from continuum processes, primarily doubly-radiative Bhabha events for K tags and $e^+e^- \rightarrow q\bar{q}$ for other modes. In order to correctly estimate their sizes, we take a data-driven approach by performing an unbinned maximum likelihood fit to the two-dimensional distribution of $\Delta E^{\gamma\gamma}$ versus ΔE^{tag} , as shown in figure 3. We use $\Delta E^{\gamma\gamma}$ distributions rather than $M_{\text{BC}}^{\gamma\gamma}$ distributions as the background from non- $D\bar{D}$ decays is more easily addressed in the fit. Also, the background from $D^0 \rightarrow \pi^0\pi^0$ peaks in $M_{\text{BC}}^{\gamma\gamma}$ at the same place as the signal does, whereas it is shifted in $\Delta E^{\gamma\gamma}$. The fitting ranges are $|\Delta E^{\gamma\gamma}| < 0.25$ GeV and $|\Delta E^{\text{tag}}| < 0.1$ GeV. These wide ranges are chosen to have adequate statistics of the continuum backgrounds in our fit. For the signal and the $D \rightarrow \pi^0\pi^0$ background, we extract probability density functions (PDFs) from MC simulations. For the background from continuum processes, we include a flat component in two dimensions, allowing the normalization to float. The contribution from D^+D decays is completely negligible. We model the background from other $D^0\bar{D}^0$ decays with a pair

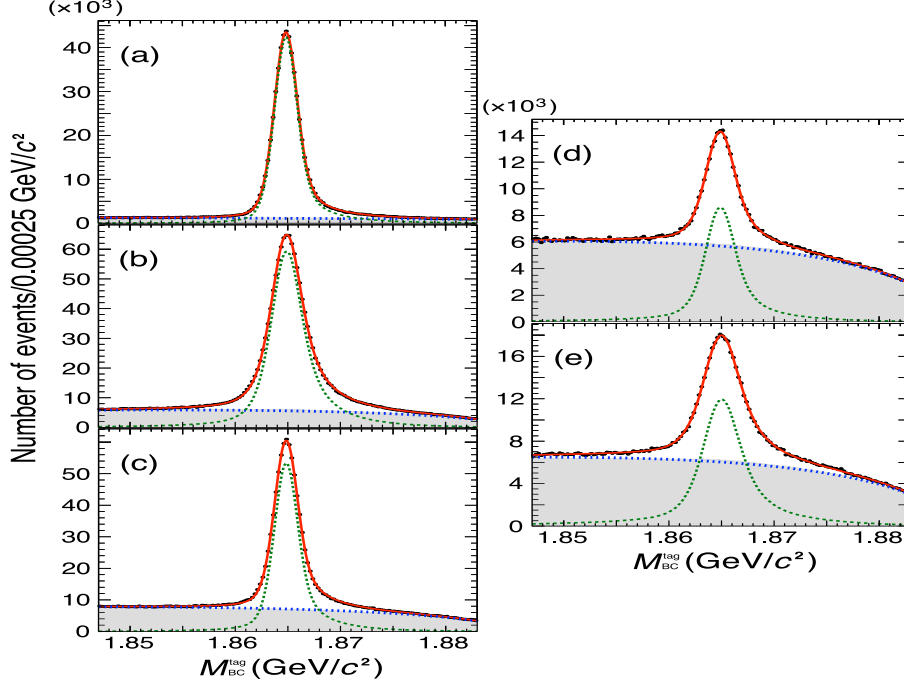


Figure 2: Fits (solid line) to the $M_{\text{BC}}^{\text{tag}}$ distributions in data (points) for the five D^0 tag modes: (a) $K^+\pi$, (b) $K^+\pi\pi^0$, (c) $K^+\pi\pi^+\pi$, (d) $K^+\pi\pi^+\pi\pi^0$, and (e) $K^+\pi\pi^0\pi^0$. The gray shaded histograms are arbitrarily scaled generic MC backgrounds.

of functions. In the ΔE^{tag} dimension we use a Crystal Ball function (CB) [18] plus a Gaussian, and in the $\Delta E^{\gamma\gamma}$ dimension, we use a second-order exponential polynomial function. In our nominal fitting procedure, we fix the following parameters based on MC: the power-law tail parameters of the CB, the coefficients of the polynomial, and the mean and the width of the Gaussian function. The normalization for the background from all other $D^0\bar{D}^0$ decays is left free in the fit, as are the mean and width of the CB and the ratio of the areas of the CB and Gaussian functions. Figure 3 shows projections of the fit to the DT data sample onto $\Delta E^{\gamma\gamma}$ (top) and ΔE^{tag} (bottom).

The fit yields $N_{\text{tag},\gamma\gamma} = (1.0^{+3.7}_{-2.3})$, demonstrating that there is no signal for $D^0 \rightarrow \gamma\gamma$ in our data. This corresponds to $\mathcal{B}(D^0 \rightarrow \gamma\gamma) = 3.8 \times 10^{-6}$ including the systematic uncertainties. If the systematic uncertainty were ignored in setting this limit it would be reduced by 0.1×10^{-6} .

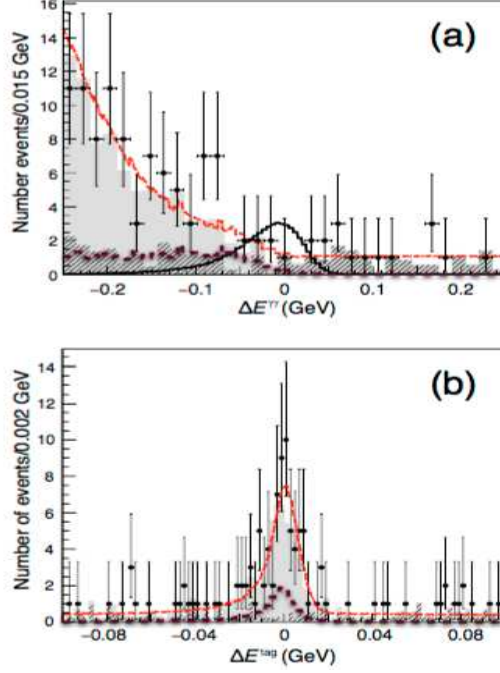


Figure 3: Fit to the DT sample in data (points), projected onto $\Delta E^{\gamma\gamma}$ (a) and ΔE^{tag} (b). The dashed lines show the overall fits, while the dotted histograms represent the estimated background contribution from $D^0 \rightarrow \pi^0 \pi^0$. The solid line superimposed on the E projection indicates the expected signal for $\mathcal{B}(D^0 \rightarrow \gamma\gamma) = 10 \times 10^6$. Also overlaid are the overall MC-estimated backgrounds (gray shaded histograms) and the background component from non- $D\bar{D}$ processes (diagonally hatched histograms).

5 Summary

In summary, by analyzing 2.92 fb^{-1} data collected at $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector at the BEPCII collider, we search for the FCNC decays $D^0 \rightarrow \gamma\gamma$, $D^+ \rightarrow h^+ e^+ e^-$ and the LNV decays $D^+ \rightarrow h^- e^+ e^+$. No signal excess is observed. As a result, we set the upper limits on the branching fractions for these decays at a 90% CL. The results for $D^+ \rightarrow \pi^+ e^+ e^-$ and $D^+ \rightarrow K^- e^+ e^+$ are significantly improved than the previous restrictions, while those for $D^+ \rightarrow \pi^- e^+ e^+$ and $D^+ \rightarrow K^+ e^+ e^-$ are comparable with the world best results. The result for $D^0 \rightarrow \gamma\gamma$ is consistent with the upper limit previously set by the BABAR Collaboration [19]. Our result is the first experimental study of this decay using data at open-charm threshold, where the backgrounds from non- $D\bar{D}$ decays can be effectively suppressed. The resulting upper limits are still above the Standard Model predictions, no hints for New Physics have been found yet.

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